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THE INFLUENCE OF SIMULTANEOUS AND SEQUENTIAL DISPLAY MODES ON HUMAN INFORMATION-TRANSFER BEHAVIOR

Eckehard Behr

Human Engineering Laboratory
Aberdeen Proving Ground, Maryland

August 1974

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This experiment investigated how two display modes affect human information-transfer performance. Subjects read test numbers from a cathode-ray tube and entered them into a keyboard. The numbers appeared either one digit after another (sequentially) or all digits at once (simultaneously). There were three number-lengths (four, six, and eight digits) and three exposure times (100, 500, and 1000 msec.). Performance was evaluated from errors and response times, and subjects' transfer strategies were examined.

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20. Abstract

Simultaneous displays transferred digits more effectively than sequential ones. Performance was better with shorter numbers or longer exposure times. Subjects transferred only four to five digits accurately, and only when the exposure time was 500 msec. or longer. Their channel capacity approximated 13 bits.

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Eckehard Behr

August 1974

APPROVED: John D. Weisz

JOHN D. WEISZ
Director
U. S. Army Human Engineering Laboratory

U. S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland

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INTRODUCTION

There have already been many meaningful approaches to investigate the unanswered questions in the field of human information input, processing and transfer. Even so, human factors engineers still confront difficult problems in choosing the best display modality for presenting information. Computers nowadays become increasingly integrated into modern technology. Accordingly, human factors research is focussing more and more on the respective interactions and interfaces of the human operator and the computer. In designing computer displays, input devices like keyboards become critical links in inputting and transferring information. Unless display modalities are designed with sufficient care, they can degrade the performance of the whole man-machine system; poorly designed displays can be as inefficient as an incompatible or disordered keyboard.

Often we overestimate human performance limits and human mental capacity, particularly when certain levels are required to match the computer's capabilities. When we do, the whole system can hardly achieve the reliability that is required. To optimize the man-computer system, we must assign tasks to the man only when his capacity is superior to the computer's. We must avoid requiring the man to perform tasks when his abilities are obviously inferior to the computer's, or when the display modalities are not fitted to the man's limited perceptual abilities. To achieve optimal information transfer, any screen or device that displays information to the human operator must meet a very basic requirement: the information must be presented in a form that can be assimilated by the limited range of man's physiological and psychological abilities.

In spite of wide-ranging automation, there are still many situations where automation cannot replace man as a link in data processing. Sometimes the man must do tasks even though he does not perform them very efficiently; he remains the weakest link within this chain. One such task is manually feeding data into a computer system. Data cannot always be entered automatically. Usually these data are not generated by the operator himself; he must acquire them from elsewhere, either from displays, or from lists, or from other information sources. Although the man often has to process these data – decoding them, or selecting particular data from a complex array – many tasks involve a simple transfer.

The present experiment will study these transfer tasks, investigating input strategies and transfer behavior. In this case, transfer will mean immediately removing or shifting information from one medium to another. The operator's task will require reading the data that are presented and then, without processing them, immediately keying the data into the computer. The operator may have to store the data –hold them in his memory– while he is keying them. This kind of transfer process usually demands both speed and accuracy, so the criteria for evaluating performance will be both entry time, on the one hand, and errors, on the other hand. If the displayed data are entered very rapidly, the operator's processing may merely involve transfer. However, slower responses may verge on times that require short-term memory as well, under certain conditions.

The subject's task will probably require a combination of both memory and perceptual processes. With full recognition of the very complex nature of perceptual as well as mnemonic processes, the following discussion attempts to deal with these complex interactions in simplified terms, so they can be investigated experimentally.

Following the conventional distinction, we will differentiate two sorts of human memory. The long-term memory means storing information indefinitely, for protracted periods of time. But when information is stored only briefly, for between a fraction of a second and a few seconds, the process is called short-term memory.

As a matter of fact, memory or storage ability is not the most reliable feature of human performance. The man's storage ability cannot compete successfully with a computer's. When men must serve as important storage links in the man-computer system, they will always degrade the whole system's reliability.

So if humans must unavoidably be assigned tasks involving long-term or short-term memory, there should be some provision for helping the operator do what his task requires. This means that all displays should be designed to transmit information as effectively as possible, in the optimum modalities and arrangements, and that the computer's entry devices should also be optimized. The entry devices themselves as essential parts of the man-computer system, obviously demand thoughtful consideration; however, this area is beyond the scope of the present investigation.

The more carefully information displays are arranged, and the more closely these arrangements are fitted to human perceptual abilities, the better the whole system's output will be. Although this aim may sound obvious, our understanding of the best ways to arrange and display information is still far from complete.

As pointed out before, transfer processes usually require high speed. This demand highlights the necessity for an optimal display modality. Consequently, the present investigation aims to determine whether certain particular ways of displaying information are superior to others. Evaluating the different display modes implies measuring subjects' (Ss') performance while using display modes as the independent variable. That, in turn, means that the Ss' performance in different modes should first be analyzed, then quantified and evaluated. These measurements of output with different display modes should indicate the best way of arranging information on the display. Regarding the possible strategies Ss might apply, it is fundamental to know how extensively these simple transfer tasks will involve human short-term memory. How efficiently information can be transferred will essentially depend on how long it must be stored between perception and completing the keying action.

By now we know that, the longer information must be stored—and the more storage is disturbed by noise or other tasks—the more the output will deteriorate.

The present investigation, then, attempts to determine whether it is possible to shorten storage time—and thus to reduce errors--by modifying the display modality.

THEORETICAL REMARKS

Theories about short-term memory deserve at least brief review, as background for understanding the implications that simple transfer and short term memory have for display modes. The recent literature proposes a variety of ways to interpret the operator's errors. These interpretations usually make assumptions about the strategy an individual uses to deal with this kind of information.

Among others, Brown (1959) and Crossman (1960) report that, when an individual stores information in the short-term memory, he is really storing both items of information and their order. Yet, as Conrad (1965) points out, item and order information are not absolutely independent. In presenting his somewhat simplified model, Conrad states that there is a fixed input order, which is encoded only by the properties of individual items. He concludes that memory models do not imperatively "need a mechanism which could transpose the order of items in storage". Conrad points out that, in tasks fully involving the short-term memory, information is retrieved from the store in the same order as it was entered.

Generally, Conrad (1965) concludes that any mistake is somehow caused by a masking or disturbing process. These interfering processes presumably occur somewhere between the perception (i.e., entering data to the memory) and retrieval from the memory. In a more elaborate model, the author assumes a specified number of boxes which represent the serial positions of the different items in a message. According to Conrad, the items enter the boxes in order of their perception. When the S recalls, he simply picks out the contents of the different boxes, starting anywhere in the sequence.

The contents of the different boxes are not interchangeable. Conrad indicates that the probability of correct recall depends on several factors: the number of boxes to be read, the signal-to-noise ratio within each box, and the discriminability of the items in the store. Probability of correct recall does not seem to depend on how large the vocabulary is, or on the amount of "order information" the sequence contains. Various studies--such as Conrad and Hull (1968), Burrows (1972), and Murdock (1968)–have shown that varying display modalities, such as visual versus audible, can have a considerable effect on retrieval. However, this report will consider only the visual modality.

Some authors evidently explain short term storage in terms of auditory (or even semantic) encoding principles. Craik (1968) and Baddeley (1966) attribute retention errors to acoustical confounding, much as Conrad (1964) does. These authors propose a theory to relate short-term and long-term memory. It pictures the individual first retrieving information from the short-term store, which has limited capacity and codes items acoustically. Afterwards, he checks the relevant areas of the long-term memory, which has different storage characteristics based partly on semantic coding. The short-term memory is described as highly sensitive to acoustical confusion–particularly when there is background noise (Baddeley, 1968), and even if the information is displayed visually.

Integrating the various findings leads to a more detailed, functional theory with input, storage, and retrieval elements. Modifying Norman's (1966) model slightly, there are three distinguishable steps:

1. Acquisition describes the initial strength of items in the memory. It depends heavily on mode of presentation, exposure time, and rate and amount of information. Coding mode must also be related to acquisition.

2. Retention means the rate at which information in the memory is lost. Deterioration of the memory trace seems to depend on activities during the storage period, as well as on environmental noise, and on all of the events transpiring between presenting the critical item and recalling it.

3. Retrieval refers to the strategy the subject uses to draw on memory traces and select a response. Retrieval probably depends on how much the retrieval cues are overloaded, since they must be discriminable and memorable at the same time.

All of this discussion leads inescapably to a single conclusion: the faster an information-transfer transaction is completed– that is, the less time there is between displaying a message to a subject and asking him to reproduce it–the less errors he will make. In terms of memory, this means that lightening a transfer task's reliance on memory reduces the opportunities for malfunctioning storage elements to cause errors.

Some preliminary investigations minimized the role of memory by using the fastest response possible: reading numbers from a display, and immediately reciting them aloud.

PILOT STUDIES

A simple experiment was conducted to evaluate the S's ability to transfer information in a very simple mode. It attempted to determine the limits of the S's ability by simply having him read aloud numbers of various lengths, which were displayed on a cathode-ray tube (CRT) for different exposure times. The numbers displayed had four, six, or eight digits, and they were displayed for 500 and 1000 milliseconds (msec.), with off-times of five seconds between numbers. The Ss' verbal responses were recorded on magnetic tape. The display program was controlled by a computer. Unlike the main experiment to be described later, this pilot study did not require any major sensorimotor coordinative task. No delay of any kind was imposed on the S's response; as soon as the S perceived the information from the display, he could begin speaking it immediately, thus minimizing storage time.

RESULTS OF THE PILOT STUDIES

Absolute Performance

Errors were used as a rough qualitative criterion. Each time the S failed to read the displayed number correctly, he scored an error.

The first independent variable exposure time– produced a considerable and highly significant effect on performance. Regardless of number of digits, Ss made many fewer errors when the numbers were presented for 1000 msec., than when they were shown for only 500 msec. (Figure 1).

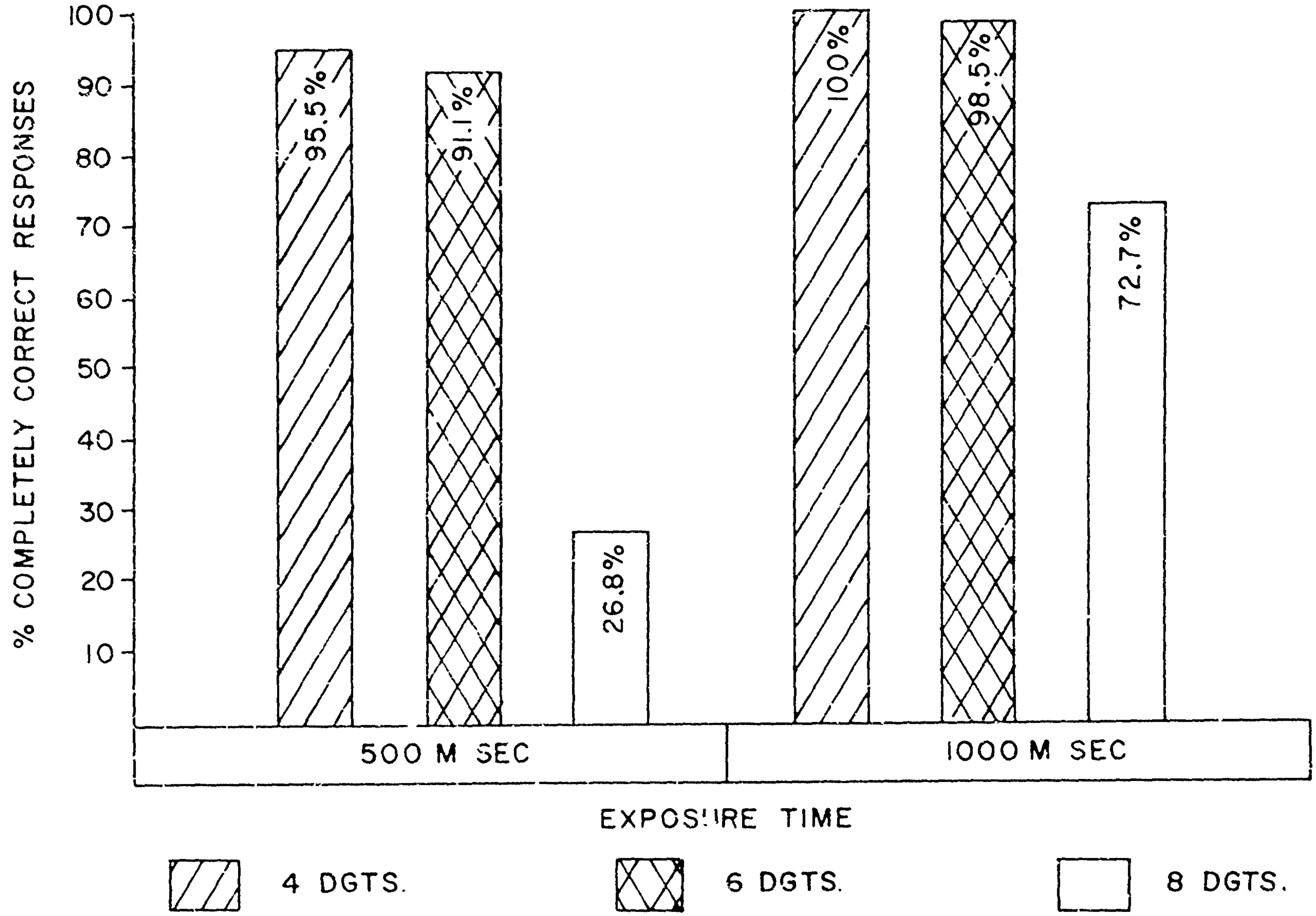

Fig. 1. Absolute performance during pilot study—average percentage of completely correct responses for each exposure time and number length.

The other independent variable—number length—also had an important effect on performance. All Ss responded correctly when they saw four-digit numbers for 1000 msec. Even with the 500-msec. exposure time, they made only very few errors. The interaction between the two independent variables was more apparent with the six-digit numbers. When these numbers were shown for 1000 msec., Ss made only 1.5 percent errors. But with the 500-msec. exposure time, they made considerably more errors (8.9%). The difference was even more pronounced with the eight-digit numbers: 27.3 percent errors for the longer exposures, nearly tripling to 73.3 percent with the shorter exposure-time.

Relative Performance

To allow more precise measurement of how well the Ss dealt with these simple information transfers, the Ss' responses were then scored on a graduated performance scale. Instead of scoring each number in an all-or-none fashion, each digit was scored separately. This procedure gave each S's total number of correct digits, which was then converted to a percentage (Figure 2), and called relative performance. These data show that the Ss achieved a relatively high level of correct responses for the four-digit and six-digit numbers with long exposures, and for the four-digit numbers with the 500-msec. exposure.

Because relative scoring allows partial credit for numbers that absolute scoring would call completely incorrect, relative scores are usually higher than absolute scores. For example, with eight-digit numbers and the short exposure time, Ss averaged only 26.8 percent absolutely correct, but 77.5 percent relatively correct. The same sort of difference appears with the long exposure time. Larger differences between relative and absolute percentages are mostly (but not entirely) due to incomplete answers.

CONCLUSIONS OF THE PILOT STUDY

Because differences between relative and absolute percentages (Table 1) seem to reflect omitted digits, abrupt increases in these differences suggest a discontinuity where difficulty increases suddenly. Under the comparatively simple modes of these test conditions, there seems to be a threshold in number lengths, below which Ss tend to respond correctly, but beyond which they make relatively many errors. The data from the pilot study seem to indicate that this threshold level averages about six digits when Ss read numbers from a display and recite them immediately, with minimal reliance on storage in memory.

There is likewise a strong indication that 1000 msec. of exposure is sufficient to transfer that much information. Both four-digit and six-digit numbers are repeated almost 100 percent correctly with the 1000-msec. exposure time. The shorter exposure time does degrade accuracy, however; at 500-msec. exposure, responses to the six-digit numbers were only 91.1 percent correct. It seems even clearer that 500 msec. is too short an exposure to transfer an eight-digit number correctly. On the average, only about six of the eight numbers—77.5 percent—were spoken correctly. Doubling the exposure time to 1000 msec. seemingly allowed Ss to transfer an average of one more digit correctly (85.9 percent of the eight digits).

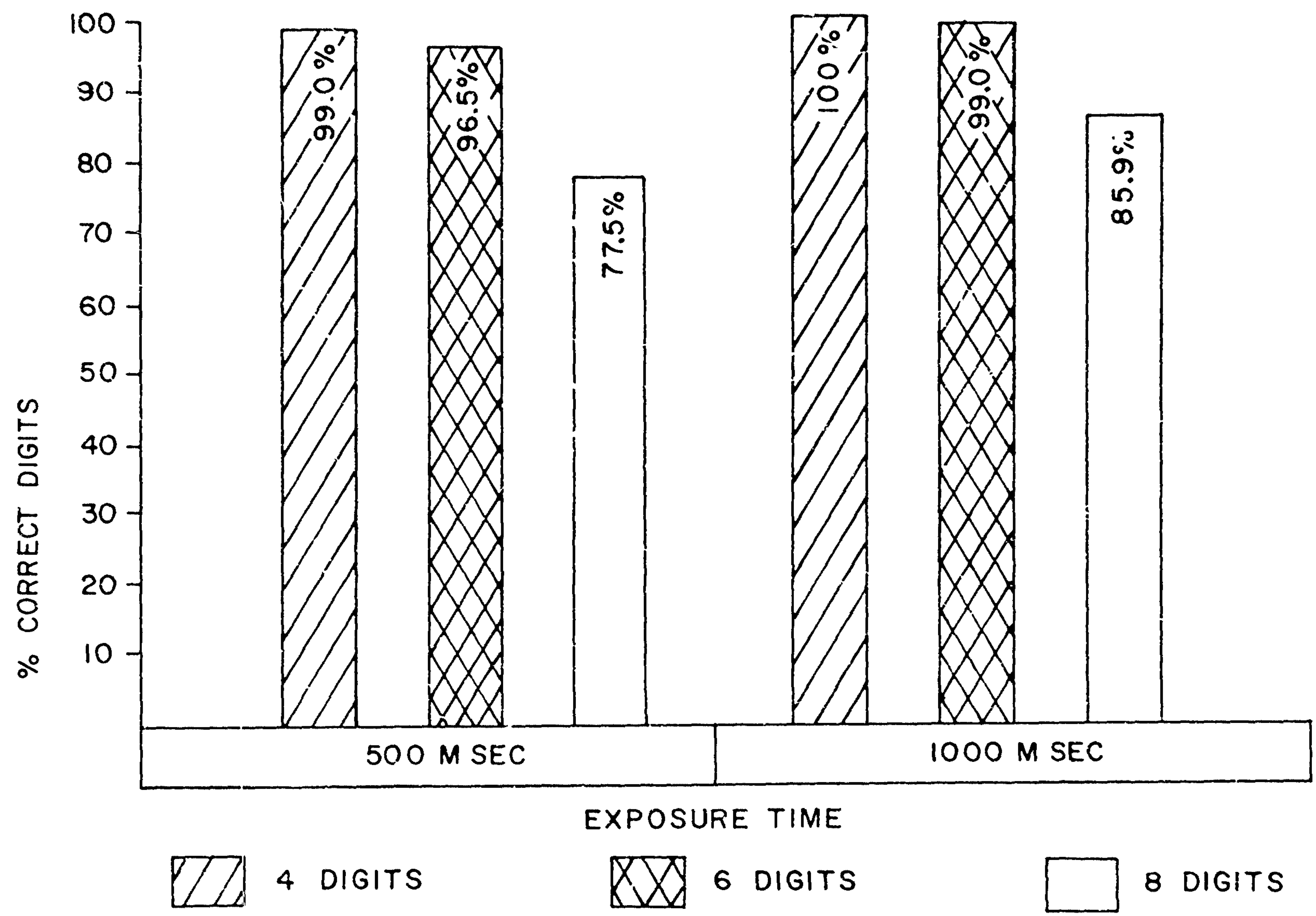

Fig. 2. Relative performance during pilot study – average percentage of correct digits for each exposure time and number length.

An analysis of types of errors generally confirms the Ss' difficulty in reciting numbers longer than six digits. Most of the errors were termed "cuts"–omitting one or more digits, typically the last four. These errors may indicate the S's strategy was to be as correct as possible in repeating as much of the number as he could. Thus Ss may have simply ignored digits they knew they could not deal with or store. The next most frequent category of errors was "subs," in which Ss substituted an incorrect digit for the right one. Other errors included inversions ("inv") which changed the sequence of two or more digits; skips ("skp") that omitted a digit within the number; and combinations of errors, or multiple errors. All of these latter errors–substitutions, inversions, skips, and multiple errors–probably indicate that the Ss tried to cope with the task without following any particular strategy.

One of the pilot study's most interesting results, however, concerned changes in the way Ss recited numbers. The Ss used very individual ways of grouping digits when reading numbers. Some Ss always read digits singly. Others came to speak in groups of two, or alternated between giving digits singly and in groups of two. However, none of the Ss recited digits in groups of three. One particular effect seemed meaningfully related to stress. Whenever the test situation became more stressful–because of longer numbers, or shorter exposure time, or especially with the combination of both–the Ss seemed to shift over to reciting numbers singly. This effect provided one basis for the main investigation's hypothesis.

TABLE 1

Absolute and Relative Performance Measures for Reciting Task in Pilot Study

Measure	500 msec.			1000 msec.		
	4-digit	6-digit	8-digit	4-digit	6-digit	8-digit
Absolute:						
Numbers Completely Correct	99.5%	91.1%	26.8%	100.0%	98.5%	72.7%
Relative:						
Digits Correct	99.0%	96.5%	77.5%	100.0%	99.0%	85.9%
Difference	0.5%	5.4%	50.7%	0.0%	0.5%	13.2%

MAIN EXPERIMENT

The pilot study had investigated the fastest sort of response that could be made in a simple transfer task. The main experiment then progressed to studying a more realistic response: having Ss enter the displayed information into a keyboard. It attempted to answer the question of whether transfer is affected when a manual keying response prolongs transfer/storage times.

It has been indicated previously that this experiment simulates real tasks where human operators have to read information from a list or a CRT, and enter it into keyboards. Consequently, the main experiment evaluated whether different display modes affect transfer, and, if so, which display mode fosters the best transfer behavior.

This test aims to improve the conditions for human transfer performance, by finding how three display variables limit human information processing.

DISPLAY MODE

In terms of input variables, transfer behavior depends heavily on basic physical factors such as brightness level, contrast, character shape, and size. On the other hand, factors like exposure duration, grouping of information, and density of information– to mention only a few–affect the individual's psychological ability to cope. Basically it is true that information displays must be consistent with human sensory abilities, both physiologically and psychologically, before they can be processed further.

One way to improve transfer and storage performance is, presumably, "preparing" the information for entry into the memory. Information should be presented in directly usable form, minimizing requirements for Ss to decode it before entering it into the memory.

The pilot study had established that, under difficult conditions, such as time stress in number-telling tasks, Ss typically shifted to speaking numbers singly. Under less-trying conditions, the Ss usually gave more two-digit groups. For example, a low-stress S giving an eight-digit number might read a two-digit group, a single digit, two more two-digit groups, and a final single digit.

From observing these behaviors, it appears that the way digits are grouped, or "chunked," has important effects on transferring them. However, it is not yet clear which grouping would be the most effective. It seems reasonable to speculate that Ss would transfer information more efficiently if the displayed numbers could be grouped as Ss would group them when reciting them. Thus, preprocessing the digits by grouping them—whether temporally, or by spacing, or even by punctuating might well simplify the transfer, relieving the S of unnecessary work, and thus improving his output. But while enforcing a particular sort of grouping should enhance performance if digits were grouped properly, it is also quite possible that unfortunate groupings could degrade performance. On the other hand, it seems noteworthy that stressed Ss tended to abandon grouping entirely, retreating to handling each digit individually. This finding may indicate that single digits constitute the simplest or most primitive grouping. Clearly, too little is known about the effects of grouping, and the first step in understanding it is demonstrating whether or not grouping affects transfer significantly.

To assess the effect of grouping in its most elementary form, the main experiment compared only two modes—one which imposed a form of grouping on the Ss, and another which did not. The first mode displayed test numbers one digit at a time, in sequence; it is called the sequential mode. The other mode, termed the simultaneous mode, followed the more-usual practice of showing all the digits at once.

NUMBER LENGTH

The literature provides a wide variety of data about human ability to handle information. Various results show that the upper limit of short-term storage capacity is approximately eight digits. Eight digits have therefore been established as the greatest number length to be displayed. To find out how transfer depends on the amount of information to be transferred, Ss were also asked to transfer six-digit numbers and four-digit numbers.

EXPOSURE TIME

In the traditional sense, performance must always be defined in terms of the times involved. The main experiment varied exposure times, to estimate how much time Ss need to store information for processing. It used three exposure times—100, 500, and 1000 msec.—to assess the shortest time needed to store defined amounts of information.

To equate input conditions for the simultaneous and sequential modes, both modes must present the same density of information: that is, the same exposure time per digit. The amount of information displayed per unit time must be the same for both modes. Thus, presenting one digit for a very short time is equivalent to displaying more digits for a longer time. For instance, showing four digits for 100 msec. represents the same information density as displaying a single digit for 25 msec.

PERFORMANCE CRITERIA

It is always difficult to measure and evaluate human mental performance. Since purely physical measures are not applicable, the experimenter must develop a more-or-less arbitrary approximation which takes both quantity and quality into account. As in the pilot study, the main experiment used both absolute and relative criteria. The absolute measure reflected, once again, how many numbers were entered completely correctly. The relative measure, expressed as the percentage of all displayed digits that were keyed correctly, compared the S's performance with perfect transfer. Effectiveness of transfer can then be evaluated by correlating these percentages with the respective exposure times

VISUAL RESPONSE TIME

Partitioning the various components of total response time should reveal clues to the strategies that Ss use to tackle transfer tasks. Visual response time would appear to be one of the most important measures; it indicates the time required for all mental coordination that prepares the message for input to the transfer process, including perception. The visual response time was approximated by measuring the time between when a number is first displayed and when the S makes his first keying response. These visual response times were later used to explore the strategies Ss used under the different test conditions.

MANUAL RESPONSE TIME

This term, used in a special sense, estimates the time Ss needed only to enter numbers in the keyboard. Manual response time is the time between keying the first digit and pressing the "Ready" key to end the trial. Thus these manual response times measured how long Ss took to enter the second through final digits. If a S had forgotten to press the "Ready" key after completing his entry, the computer program would have ended the trial 15 seconds after the display first appeared; in fact, the experimenter's observations showed that Ss always finished their responses and pressed the "Ready" key before this time limit expired. These manual response times, as a meaningful fraction of the total response times, afforded an additional opportunity to relate experimental conditions to transfer behavior.

METHOD

Subjects

The 22 Ss (4 female, 18 males) were technical and clerical employees of the U. S. Army Human Engineering Laboratory. Their ages ranged between 20 and 45.

Apparatus

The equipment used in the test is pictured in Figure 3. It includes two IDIIOM display consoles, incorporating cathode ray display tubes driven by a Varian 620. f-100 general-purpose parallel operation digital computer with 3K of memory space. The test facility's data input equipment included a card reader and two magnetic tape units. A teletype was used to insert some input commands, and a Statos 31 printer plotter supplemented the teletype for recording output data.

The Ss' console enclosed a high-speed Dualflec display using a 21-inch by 15-inch rectangular cathode-ray tube (CRT) featuring a bonded, etched faceplate to reduce reflections, and a neutral-density filter to enhance contrast. Its control circuits allowed a 14-microsecond random positioning time, as well as small angle positioning within three microseconds. The high-speed Curviline character generator was capable of writing 96 different characters, at 10-microseconds per character.

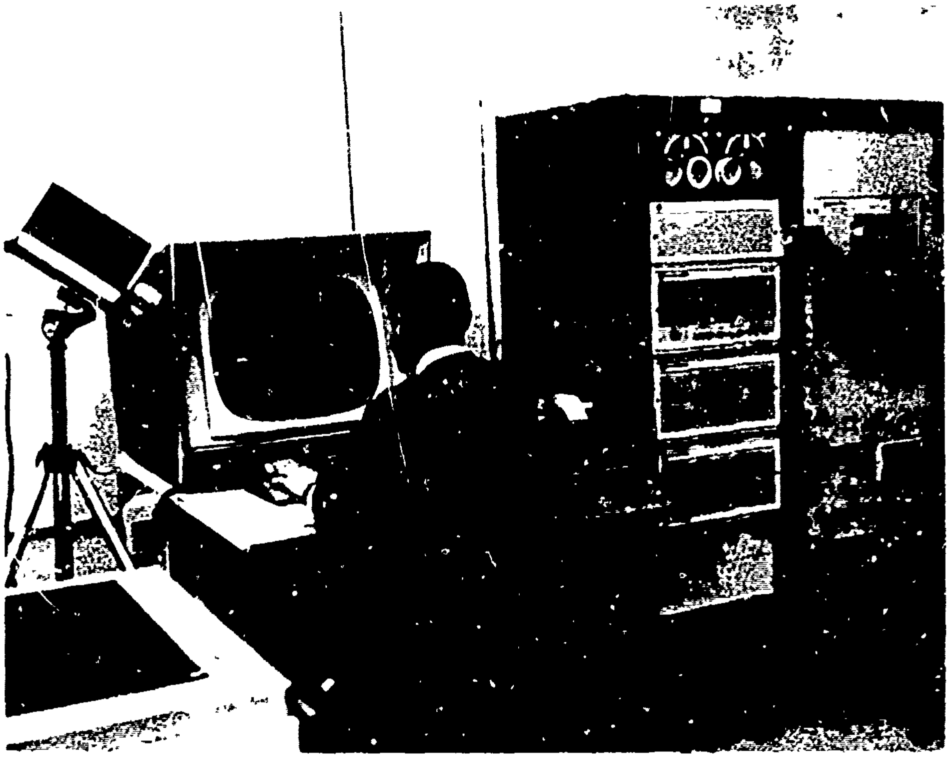

Fig. 3. Test equipment.

The characters presented in the present experiment measured 5/16-inch wide by 3/8 inch high. The style of numerals available on the CRTs was constructed from lines which form a matrix pattern (seven segments and nine strokes). These numbers (Figure 4) were easily distinguishable from each other, once the corners of the matrix pattern were rounded to enhance the numeral's appearance. A series of measurements compared the luminances of the displayed numerals and adjacent blank spaces on the CRT screen. The contrast ratio was calculated as the difference between character and background luminances, divided by character luminance, or 0.133. These measurements thus showed that character luminance averaged 7.5 times the background luminance.

For responses, a special keyboard was interfaced with the IDIIOM's keyboard register. Pressing one of the keys generated an interrupt and transmitted it to the computer, together with the number of the key pressed. This keyboard, closely resembling the familiar Touch-Tone telephone keyboard, was mounted in a stand measuring eight inches wide and ten inches deep, sloping down toward the front at a 10° angle (Figure 5). The distance between key centers was .75 inch. To the left of the button assembly there was a rectangular-shaped "ready" key.

The ambient illumination was restricted to approximately 15 foot candles.

Fig. 4. Sample display of eight-digit number, illustrating number style.

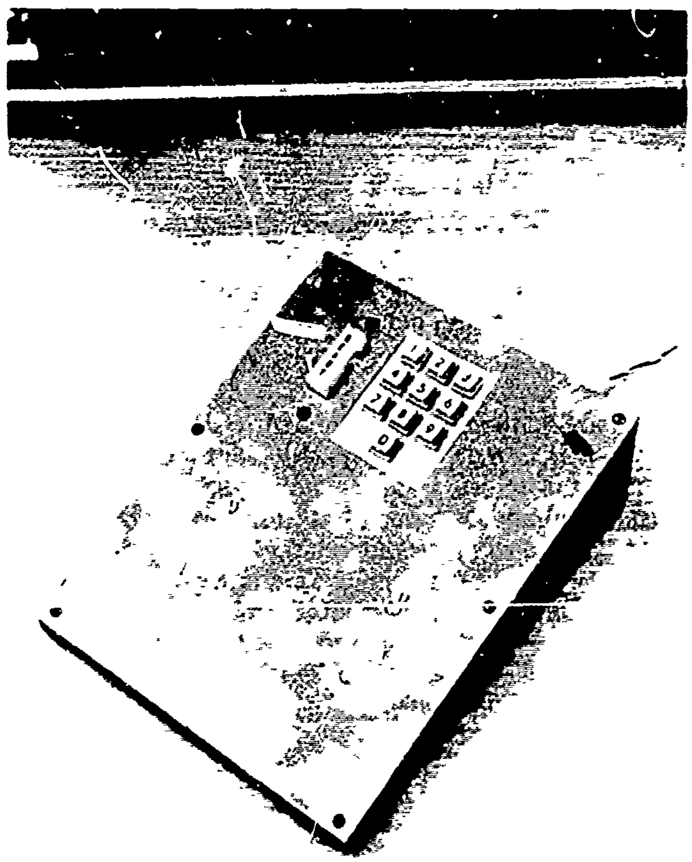

Fig. 5. Subject's response keyboard in angled stand.

The experimenter's console (Figure 6) showed both the number that was displayed to the S and his responses. A functional keyboard enabled the experimenter to control the program. By observing this display and a TV picture of the S's behavior, the experimenter monitored the S's behavior constantly.

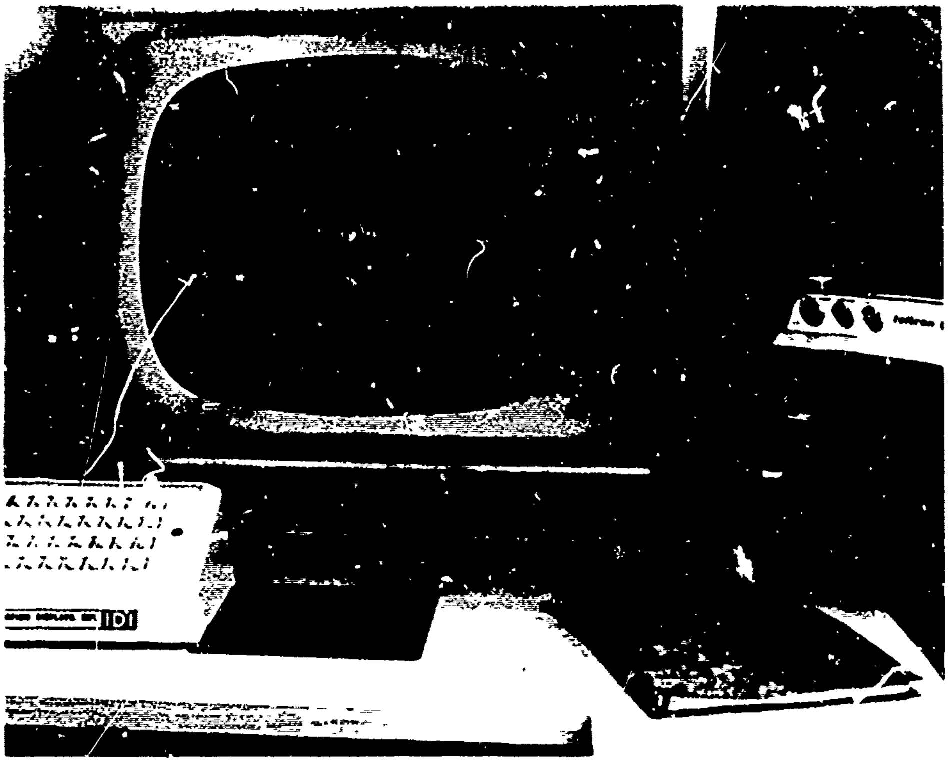

Fig. 6. Experimenter's console, displaying stimulus number and subject's response.

As pictured (Figure 3), the Ss sat in front of a CRT console and its Touch-Tone keyboard. When a number was shown on the CRT, the S entered it into the keyboard. The numbers, varying in length, appeared on the screen either simultaneously or sequentially for the predetermined amount of time. The simultaneous mode (SIM) displayed all of the digits comprising the number at once; the complete number appeared on the screen for the entire exposure time. In the sequential mode (SEQ), however, the number's digits appeared singly, one after the other; when a new digit appeared, the old one disappeared. Each digit nevertheless took the same position it would have had if all digits were shown at the same time. In either mode, the digits appeared in a rectangular frame measuring 1 5-inches by 2-inches. Regardless of length, the numbers were justified to the right margin of the frame.

Besides varying the display mode (SIM vs. SEQ), the main experiment treated two other independent variables: exposure time, and number length. There were three number lengths—four, six, and eight digits—with each number comprising random digits and no digit occurring more than once in a number. And there were three exposure times: 100, 500, and 1000 msec. Each possible combination of these variables occurred ten times, but with different numbers. In all, then, there were 2 x 3 x 3 x 10, or 180 trials.

Each of the 22 Ss was tested on these 180 trials. The set of test numbers, embodying all three lengths of numbers, were prepared in advance, arranged in random order, and stored in the computer's memory. The combinations of test variables were presented to each S in the same order.

For each trial, the computer stored the number which had been displayed, the S's keyboard entry, his response times, and any errors he made. Upon finishing his response, the S immediately pressed a "Ready" key which blanked the display for 1.5 seconds and then called up the next number to be displayed. However, if the S had not begun keying within five seconds, or if his response had not been completed after 15 seconds, the computer program would automatically have advanced to present the next number in the series. The program also included an automatic stop after each 60 trials, to give the S a short break.

Each S was given 10-15 trials for training and practice before the test proper began. The Ss were instructed to respond as quickly as they could, to ignore any errors they might realize they had made, and to press the "Ready" button as soon as they had finished keying.

RESULTS

The Ss' performance has been evaluated roughly by simply totalling their errors under the different test conditions. Here, an error was scored unless the complete keyed number was identical to the stimulus number presented; any discrepancy made the entire response incorrect.

With these error scores as performance criteria, the results show statistically significant superiority for the combination of short numbers and long exposure time, as opposed to long numbers and short exposure times.

In addition, the simultaneous mode allowed far better performance under the different conditions than the sequential mode did. This finding held true for all exposure times and number lengths. From examining the errors made within each condition, some interactions between the variables also became evident (Figure 7).

Other criteria, however, reflect a more detailed picture of the Ss' performance. A more sensitive index of their information-transfer behavior is the relative criterion—number of digits keyed correctly. By absolute right-or-wrong standards, a S who viewed eight digits but entered only six of them correctly scored one error. However, the label "error" here does not allow us to distinguish an S who entered six digits correctly from one who failed to enter any digit correctly. To provide finer graduations of measurement, we may again express the number of digits keyed correctly as a percentage of the total number of digits displayed, then the S who entered six digits correctly scored 75 percent, while the S who did not enter any correctly scored 0 percent. These relative performance indices (Figure 8) permit quantitative, rather than purely qualitative, evaluation of the S's work output.

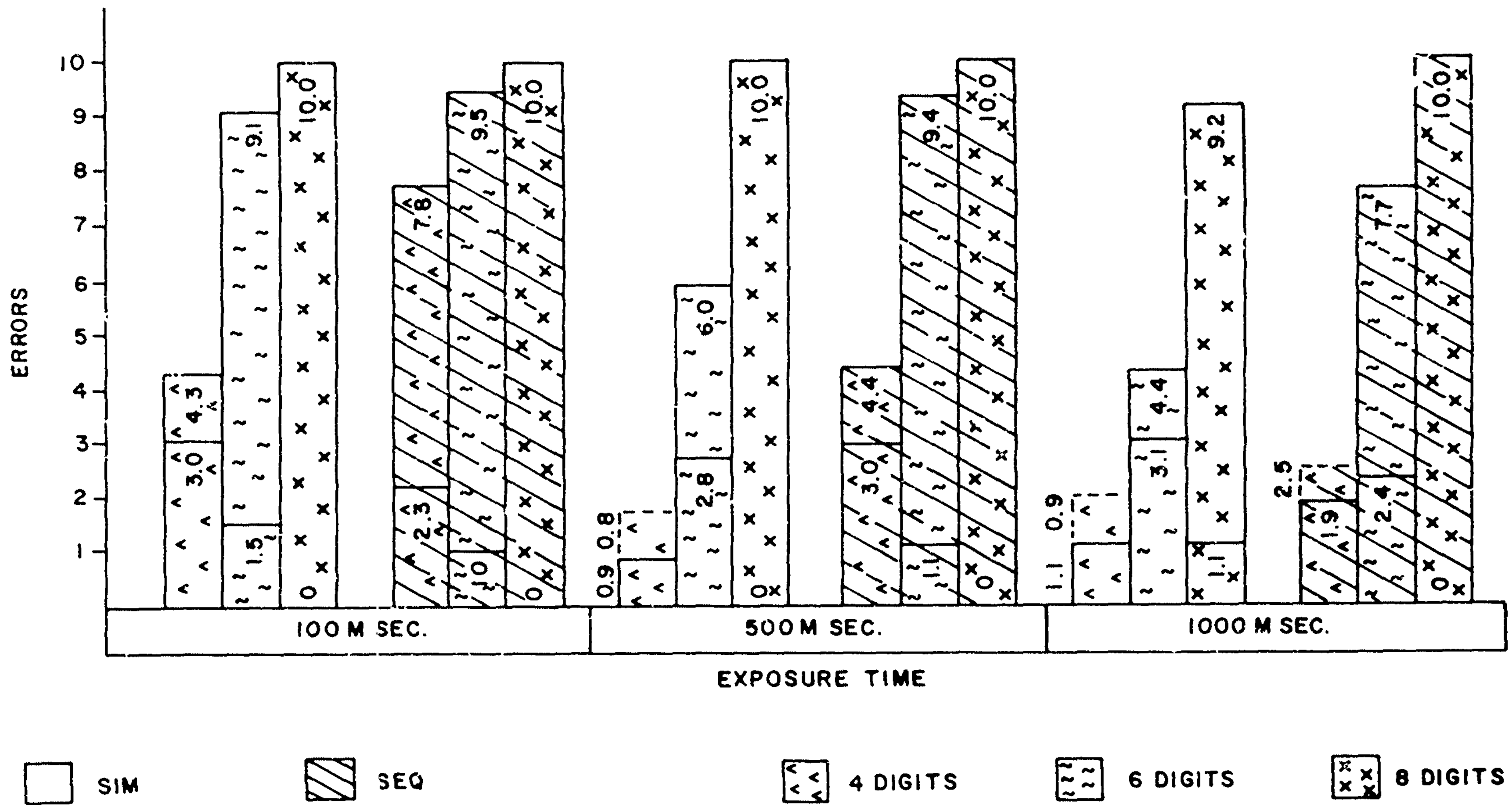

Fig. 7. Absolute performance: errors for each exposure time, number length, and display mode

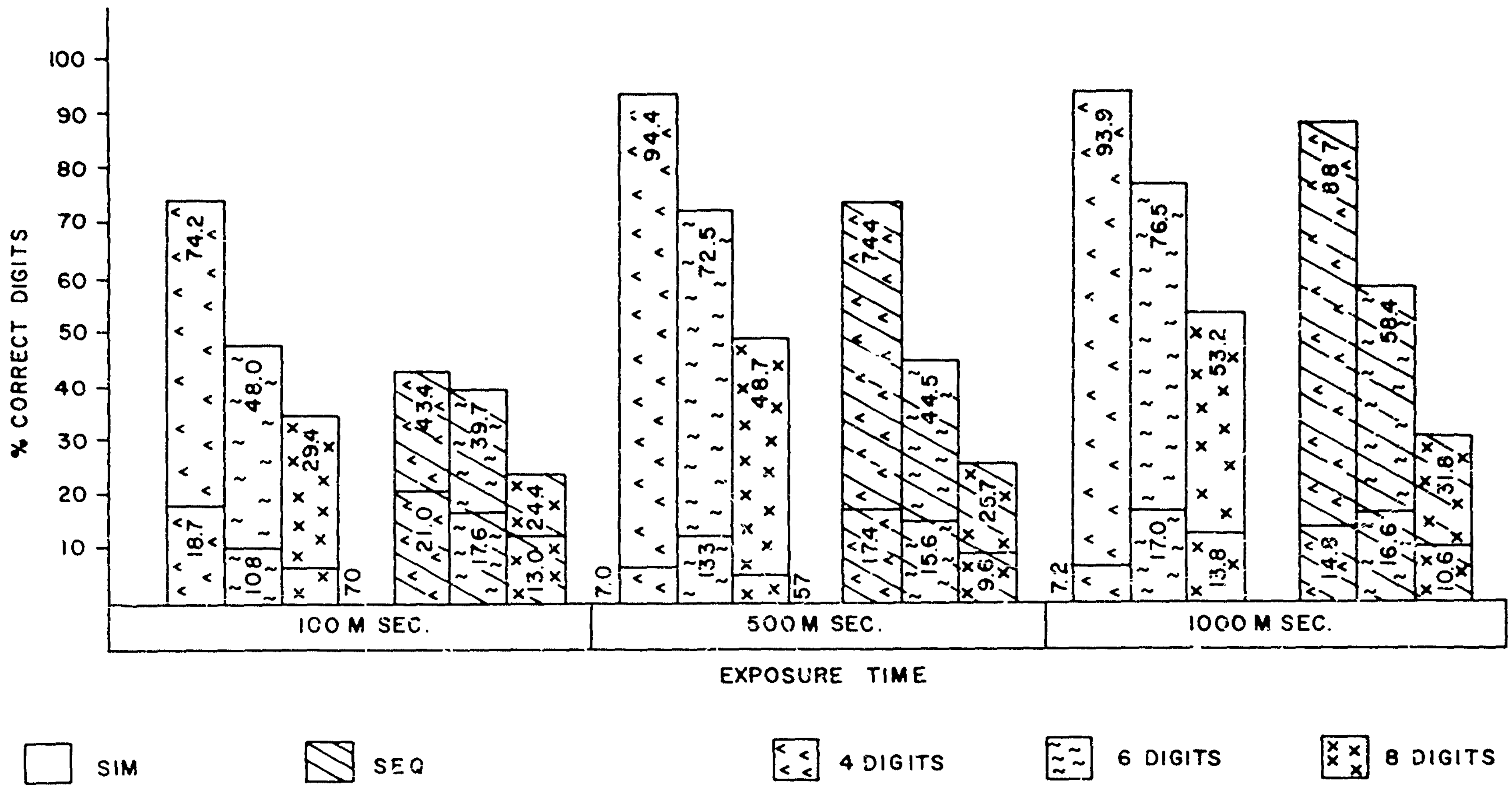

Fig. 8. Relative performance: percentage of correct digits for each combination of exposure times, number lengths, and display modes.

In terms of relative criteria, or percentage of digits correct, Ss performed best with four-digit numbers, shown for 500 msec. in the simultaneous mode; they keyed 94.4 percent of the digits correctly. When four-digit numbers were shown for twice as long (1000 msec.), the Ss transferred them nearly as effectively—with 93.9 percent accuracy. The difference between performance with 500-msec. and 1000-msec. exposure times is not significant at the .05 level. Under these conditions, apparently, 500-msec. is a long-enough exposure to transfer most four-digit numbers; lengthening the exposure does not improve transfer.

In the sequential mode, when displaying four-digit numbers for 1000 msec.—that is, displaying each digit, in order, for 250 msec.—Ss do almost as well, reproducing as many as 88.7 percent of the digits correctly. Because the percentage of digits correct is somewhat lower than for either of the simultaneous cases above, it would appear that sequential presentation requires slightly longer (perhaps 300 msec.) exposures to transfer information equally well.

In summary, these results indicate that short numbers (four digits) and long exposure times (500 and 1000 msec.) minimize transfer errors.

When the amount of information to be transferred was increased, transfer deteriorated abruptly and markedly; with six-digit numbers, shown simultaneously for 1000 msec., keyed digits were only 76.5 percent correct. This level of performance was comparable to that achieved when transferring four digits shown simultaneously for only 100 msec. (74.2 percent), or when transferring four digits shown sequentially for 500 msec. (74.4 percent). These combinations of conditions seem to balance out the effects of exposure times, display modes, and number lengths so we can speculate about their interrelationships. With a four-digit number, shown simultaneously for 100 msec. as the standard, lengthening the number to six digits requires much longer exposure for equally effective transfer; displaying half-again as much information calls for ten times as much exposure. On the other hand, showing the number sequentially, instead of simultaneously, takes five times the exposure for the same transfer effectiveness. Obviously, both number length and display mode have important effects on this performance, and these effects are seen consistently throughout the data.

With the same exposure time—100 msec.—Ss performed about as well with six digits shown simultaneously (48.0 percent) as with four digits shown sequentially (43.3 percent). Similarly, with 500-msec. exposures, Ss transferred eight-digit numbers shown simultaneously (48.7 percent) approximately as accurately as six-digit numbers shown sequentially (44.5 percent). Or, at the 1000-msec. exposure time, Ss transferred eight-digit numbers shown simultaneously (53.2 percent) almost as correctly as six-digit numbers shown sequentially (58.4 percent). Presenting digits sequentially, rather than simultaneously, seems to cost a penalty equivalent to transferring two extra digits.

As it turned out, Ss were unable to transfer numbers effectively when more than six digits (i.e., eight) were presented in the sequential mode. This generalization proved true even for the longest exposure time used in the present experiment,[1] with eight-digit numbers, the Ss were able to key only about 25 to 30 percent of the digits displayed. This accuracy is very similar to that achieved with four digits displayed simultaneously for 100 msec. (29.4 percent). Hence the decreased accuracy with longer numbers seems attributable to too-short exposures.

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[1]As a matter of fact, exposing eight digits sequentially during 1000 msec. means showing each individual digit for only 125 msec.

Differences in number length are clearly related to differences in performance under all of the test conditions except one. The Ss reached their poorest transfer accuracy when numbers were displayed sequentially for only 100 msec. While there were still important differences, the generally lower performance level tended to mask them. An analysis of variance has been calculated for the relative performance data (Table 2). Although there was considerable variation within individuals, which is not unexpected for this kind of task, there were also highly significant differences attributable to the independent variables.

TABLE 2

Analysis of Variance: Relative Performance

Source	Sum of Squares	df	Mean Square	F
Between Modes	31,249.8	1	31,249.8	160.5**
Between Number Lengths	119,808.7	2	59,904.4	308.6**
Between Exposure Times	39,847.2	2	19,923.6	102.6**
Modes X Number Lengths	84.8	2	42.4	
Modes X Exposure Times	1,726.5	2	863.2	4.4**
Number Lengths X Exposure Times	4,030.9	4	1,007.7	5.1**
Modes X Number Lengths X Exposure Times	6,187.6	4	1,546.7	7.9**
Within	73,393.	378	194.1	
Total	276,328.8	395		

**Significant at .01 level.

The two display modes proved to have more pervasive effects (Table 3) than did the differing exposure times. The coefficients of determination for these independent variables are $n_{mod} = .37$, and $n_{ex.t.} = .33$. The analysis of variance also revealed a significant two-way interaction between the display-mode and exposure-time main variables, as well as a significant higher-order interaction among all three independent variables. The interaction between modes and number length was not statistically significant, although it suggests a clear-cut trend.

TABLE 3

Relative Performance for Keying Task: Differences Between Simultaneous and Sequential Modes

	Number of Digits		
Exposure Time	4	6	8
1000-msec.	5.2%	18.1%	21.4%
500-msec.	20.0%	28.8%	23.0%
100-msec.	30.8%	8.3%	5.0%

Absolute Versus Relative Performance

Table 4 compares the absolute and relative performance criteria.

Differences between the two performance modes seem to show how the independent variables affect transfer performance. Small differences between the absolute and relative percentages indicate very effective transfer. For example, small differences are typical of the relatively "easy" and undemanding conditions, such as showing short numbers for long exposures in the simultaneous mode. In these cases, most of the numbers displayed were keyed completely correctly, and a high percentage of the digits were keyed correctly in all cases.

Larger differences between absolute and relative criteria may still represent effective performance, but they reveal overloading; the operator was unable to process the amount of information presented. While he may have entered the majority of digits correctly, he also made mistakes. There appears to be a threshold amount of information which can be transferred without appreciable error; as the information load increases beyond this threshold, relative-error percentages increase somewhat, and absolute-error percentages increase even more.

TABLE 4

Absolute and Relative Performance Measures for Keying Task: Percentage of Completely Correct Numbers, and Percentage of Correct Digits

	Simultaneous			Sequential		
Exposure Time	4-digit	6-digit	8-digit	4-digit	6-digit	8-digit
1000-msec.						
Correct Numbers	91.0%	56.0%	8.0%	81.0%	23.0%	0.0%
Correct Digits	93.9%	76.5%	53.2%	88.7%	58.4%	31.8%
Difference	2.9%	20.5%	45.2%	7.7%	35.4%	31.8%
500-msec.						
Correct Numbers	92.2%	40.0%	0.0%	56.0%	6.0%	0.0%
Correct Digits	94.4%	72.5%	48.7%	74.4%	44.5%	25.7%
Difference	2.2%	32.5%	48.7%	18.4%	38.5%	25.7%
100-msec.						
Correct Numbers	57.0%	9.0%	0.0%	22.0%	5.0%	0.0%
Correct Digits	74.2%	48.0%	29.4%	43.4%	39.7%	24.4%
Difference	17.2%	39.0%	29.4%	21.4%	34.7%	24.4%

Substantial differences between absolute and relative percentage criteria occurred primarily with the longer numbers, longer exposure times, and simultaneous display. Similar, though smaller, differences appeared even when six-digit numbers were displayed for 100 msec. simultaneously, or for any exposure time sequentially. When six-digit numbers were shown simultaneously for 500 msec., the Ss gave 72.5 percent correct digits, but only 40 percent of the complete numbers were entirely correct. This finding would seem to show that the overload threshold lies at about four digits for 500-msec. and 1000-msec. exposure times. In support of this conclusion, data for the longest simultaneous exposure times demonstrate that longer numbers were totally correct only 8 percent of the time in one case, and never correct at all in other cases. Yet under these same conditions, respectively, 53.2 percent and 48.7 percent of the individual digits were correct.

A similar trend appeared when six-digit numbers were displayed sequentially. With long exposures, Ss entered numbers totally correctly only about half of the time—and far less often when the exposure was shorter. Under these conditions the limit of transfer capacity seems to be somewhere between three and four digits.

In terms of all these findings, it is not surprising that differences between relative and absolute scores are greatest when six digits are displayed sequentially, regardless of exposure times (Conditions 8, 10, and 12). The Ss were simply unable to enter all six digits correctly; consequently the percentages of completely correct responses were very low. Nevertheless, the Ss were able to enter some three or four of the displayed digits, so their relative percentages were higher.

So far as response strategy is concerned, when an eight-digit number was displayed simultaneously, the Ss seemed to concentrate their attention on its first four digits—thus effectively doubling the exposure times for these digits. Rather than attempting to read eight digits in 100 msec., they used this same time to read only four of the digits, either singly or in groups—and possibly devoted some part of the exposure time to rehearsing the numbers they had read.

This strategy could not be used with the sequential mode. If a six-digit number was shown for 100 msec., the Ss had just 16.7 msec. to read each digit. Even when the six-digit numbers were shown for 500 msec., Ss had only 83.3 msec. to read each digit before it vanished inexorably. These very short exposure times may explain why Ss did about as well when looking at six digits sequentially, as with the seemingly more demanding task of reading eight digits shown simultaneously.

On the other hand, the eight-digit numbers shown simultaneously may have proved so difficult because, even though Ss probably concentrated mostly on the first three or four digits, they were unable to cope with the remaining digits and tended to be confused by them.

As compared to both of these two conditions—six digits sequentially, and eight digits simultaneously—Ss performed significantly better with six digits displayed simultaneously. This result would necessarily follow if Ss concentrated their attention on the four initial digits, because there would be fewer remaining, unprocessable digits to confuse them; it would become easier to locate the digits which would actually be transferred. Simply put, the Ss evidently found it easier to ignore two digits out of six than to mentally discard four digits out of eight. The real advantage of narrowing or focussing attention in this way is probably that it allows the S to double (or at least increase) each digit's effective exposure time. By restricting himself to the number of digits he has learned he can manage correctly, the S transfers information more effectively.

Rabbit (1968) has suggested another explanation of why longer numbers become so difficult to transfer. The secret of transferring numbers correctly, according to Rabbit, is that Ss must learn to shift their attention between analyzing new information and rehearsing the digits that have already been stored. While highly practiced Ss can and do learn to perform these attention shifts, it appears unlikely that the Ss used here had achieved equal mastery of this skill. When the task was difficult and demanding, as when transferring eight-digit numbers, attempts to perceive new information probably interfered with rehearsing the stored digits that had already been perceived. With both six- and eight-digit numbers shown simultaneously, the group of Ss gave comparatively large standard deviations. These seem to arise from sizable differences between individuals, probably rooted in the use of different strategies and especially in varying mastery of the attention shifts required.

Visual Response Times

We have already distinguished a component of the total keying time that is called visual response time, or "preparation time." It is the interval between when the display is first shown and when the S makes his first keying response. These visual response times (VRT), given in Table 5 shows three particularly important consequences:

1. Longer numbers give longer VRTs.

2. Longer exposure times also give longer VRTs.

3. VRTs for simultaneous and sequential modes do not differ significantly.

The visual response times were examined in an analysis of variance using log-transformed data (Table 6). In substance, it gave statistical verification of the three consequences mentioned above. It was demonstrated that visual response times for the two modes did not differ significantly. Both longer numbers and longer exposure times increased visual response times significantly (.01 level), but the effect of longer exposures was somewhat more pronounced.

Only one interaction—between modes and number lengths—reached significance at the .05 level. However, there also appeared to be some interaction between modes and exposure times, although it was not statistically significant.

These visual response data (Figure 9) show that sequential presentation does not facilitate information transfer. If presenting the digits singly had actually made it easier to transfer numbers, the sequential mode should have given faster visual response times. While visual response times were somewhat faster with sequential presentation, the modes had no statistically significant effect on visual response times.

Various data also indicate that mental processing intervened between displaying a number to the S and his keying it. Both the data and the experimenter's observations during the test support the hypothesis that Ss encode stimuli acoustically even during simple transfer tasks. Most of the Ss repeated the displayed numbers aloud before (or while) entering them in the keyboard.

With longer exposure times, Ss evidently spend more time in rehearsing or otherwise preparing the messages. Thus they appeared to take advantage of the higher redundancy made possible by longer exposures. When Ss took more "preparation" time before starting to key long numbers, it may have been because they needed longer to select and perceive the first three or four digits. This additional information processing would logically require at least slightly more visual response time.

TABLE 5

Visual Response Times (Msec.) for Keying Task

Exposure Time	Simultaneous 4-digit	Simultaneous 6-digit	Simultaneous 8-digit	Sequential 4-digit	Sequential 6-digit	Sequential 8-digit
1000-msec.	1920	2630	2770	2410	2600	2590
500-msec.	1950	2220	2440	2210	2270	2330
100-msec.	1880	2230	2270	2030	2090	2170

TABLE 6

Analysis of Variance: Visual Response Times

Source	Sum of Squares	df	Mean Square	F
Between Modes	0.01	1	0.01	0.16
Between Number Lengths	1.40	2	0.70	11.66**
Between Exposure Times	1.68	2	0.84	14.00**
Modes X Number Lengths	0.49	2	0.25	4.16*
Modes X Exposure Times	0.23	2	0.12	2.00
Number Lengths X Exposure Times	0.41	4	0.10	1.66
Modes X Number Lengths X Exposure Times	0.18	4	0.05	0.83
Within	23.50	378	0.06	
Total	27.90	395		

*Significant at the .05 level.
**Significant at the .01 level.

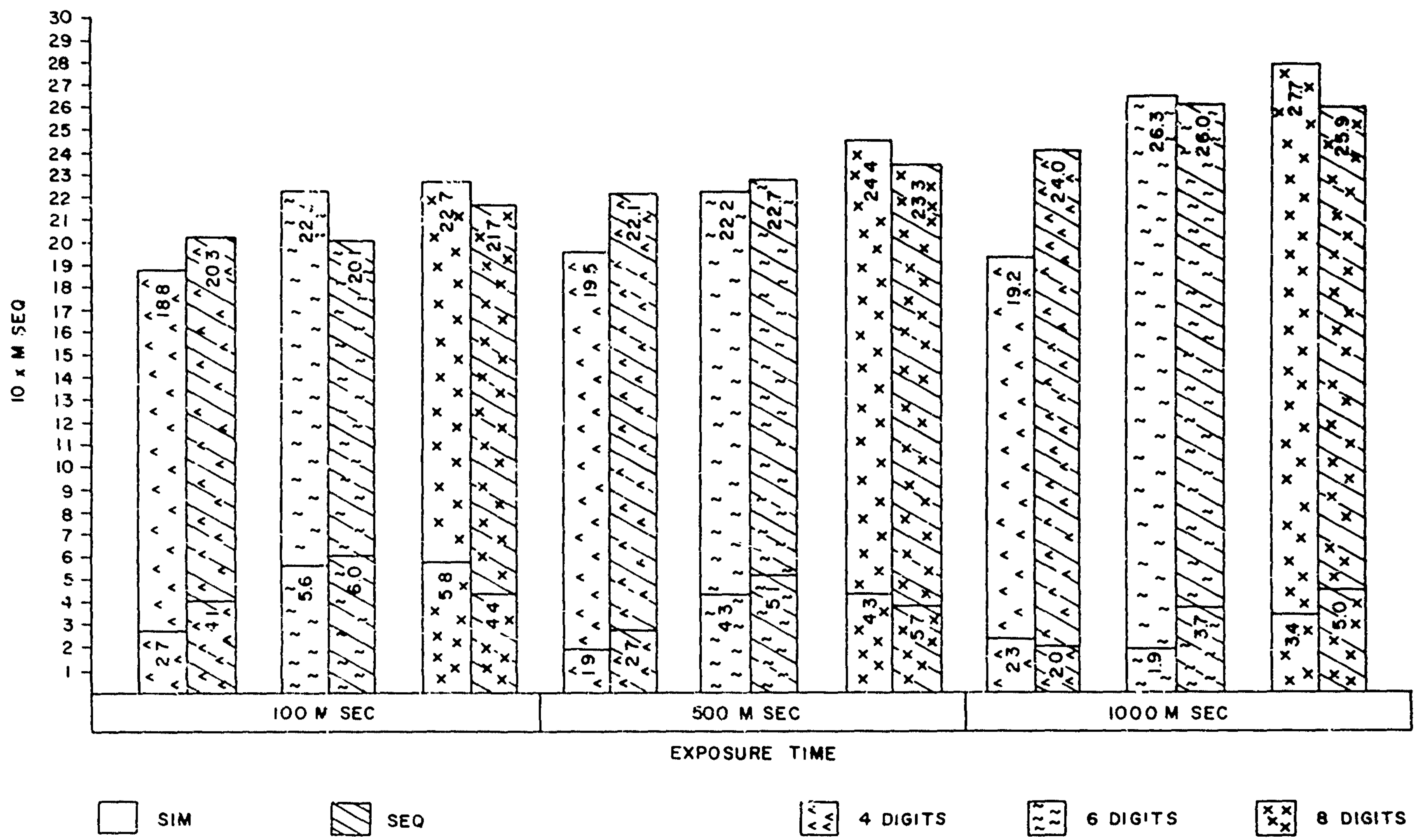

Fig. 9. Visual response times for each combination of exposure times, display modes, and number lengths.

It seems noteworthy that visual response times were slightly longer for four digits than for six digits, even though both numbers were displayed sequentially. One possible interpretation is that Ss may have felt four-digit numbers were still within their capability to transfer, but that six-digit numbers were too long; if so, the Ss may have devoted more conscientious effort to the four digit numbers, slighting the six-digit numbers as an unreasonable overload. This occurred only with the sequential mode. Therefore it probably accounts for the significant interaction between modes and number lengths.

Manual Response Time

Another component of total response time is the manual response time, which means the time between when the S keys his first digit and when he finishes entering the number. These manual response times, or overall keying times, are presented in Table 7 and Figure 10. They appear generally consistent with the other results considered thus far. Three major conclusions seem indicated:

1. Manual response times are longer with simultaneous presentation than with sequential presentation.

2. Longer numbers give longer manual response times.

3. Longer exposure times also give longer manual response times.

TABLE 7

Manual Response Times (Msec.) for Keying Task

	Simultaneous			Sequential		
Exposure Time	4-digit	6-digit	8-digit	4-digit	6-digit	8-digit
1000-msec.	1880	2840	3250	1960	2490	2530
500-msec.	1700	2610	2490	1880	2130	1950
100-msec.	1910	2090	2270	1710	2070	2190

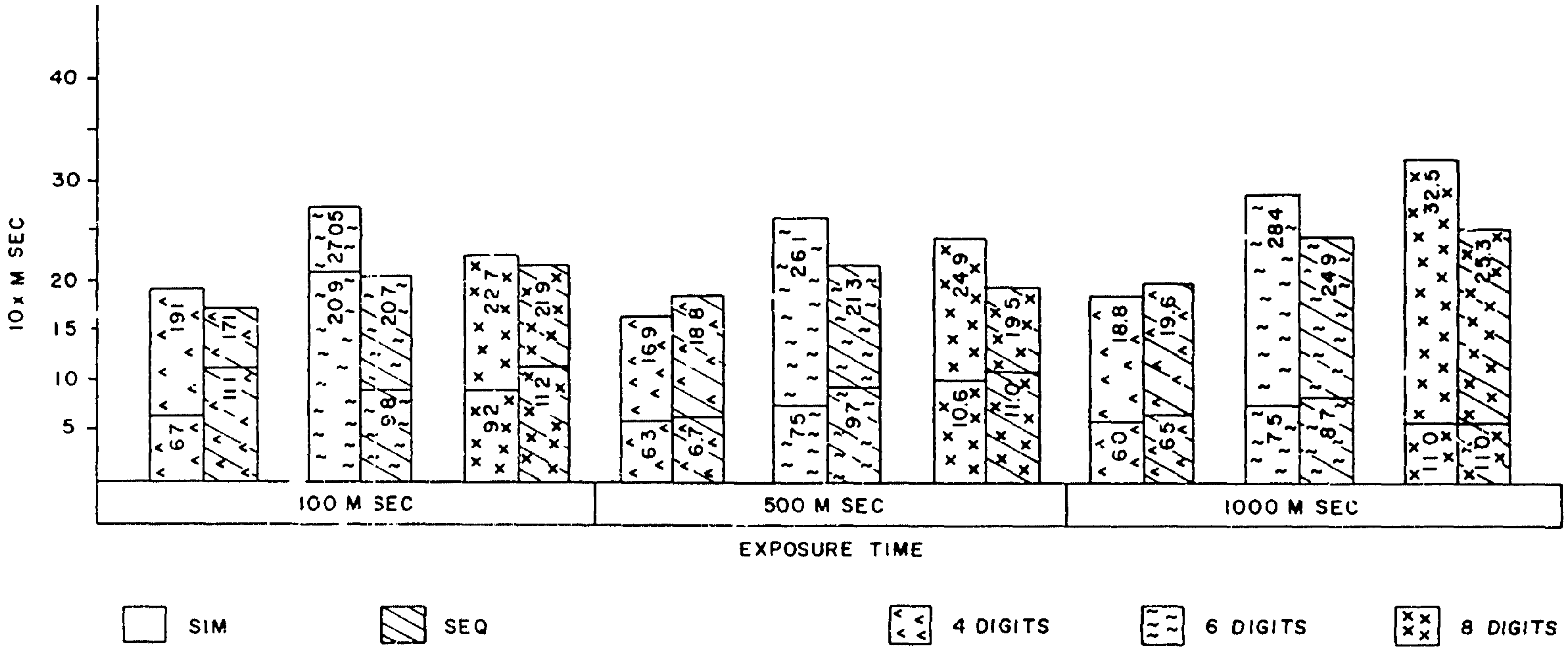

Fig. 10. Manual response times for each combination of exposure times, display modes, and number lengths.

In an analysis of variance using log-transformed data (Table 8), all three of these differences proved significant at the .01 level. Number lengths produced the largest effect on manual response times, modes were of less importance, and exposure times were still less important. Unlike the previous analysis of variance, none of the interactions reached statistical significance.

TABLE 8

Analysis of Variance: Manual Response Times
(Log-Transformed Data)

Source	Sum of Squares	df	Mean Square	F
Between Modes	1.67	1	1.67	12.84**
Between Number Lengths	4.19	2	2.09	16.07**
Between Exposure Times	2.79	2	1.39	10.69**
Modes X Number Lengths	0.29	2	0.14	1.07
Modes X Exposure Times	0.12	2	0.06	0.46
Number Lengths X Exposure Times	0.83	4	0.21	1.61
Modes X Number Lengths X Exposure Times	0.59	4	0.14	1.07
Within	50.96	378	0.13	
Total	61.44	395		

**Significant at the .01 level.

Contrary to these general relationships, manual response times for four digit numbers were shorter in the sequential mode. This effect is evidently an artifact caused by incomplete responses—that is, fewer keys to press when four digits were shown sequentially. This effect appears characteristic of test conditions which overloaded the Ss and degraded their transfer performance. Under conditions where the Ss performed relatively well for example, four digits exposed for 500 or 1000 msec.—manual response times were longer (not shorter) for the sequential mode. Thus, manual response times support the earlier observation that simultaneous presentation gives superior transfer to sequential presentation.

There is a close, obvious relationship between manual response time and relative performance. An absolute measure like keying time necessarily increases when more responses must be keyed; if longer exposure times allow Ss to transfer more digits, they consequently prolong manual response times.

Error Categories

The Ss' keying errors were analyzed to determine the types of errors they made. Based on earlier investigations of number transfer (Conrad, 1965, Murray, 1965), there appear to be six main kinds of errors:

1. A cutting error (CUT) means the S keyed in the correct digits in the correct order, as far as he went, but omitted the final digit(s)

2. The inversion type error (INV) includes all those errors where the order of two or more digits was changed (inverted).

3. The skip error (SKP) refers to errors where the S omitted one or more digits of the number (except the last one).

4. A substitution error (SUB) is scored when an S has substituted an incorrect digit(s) for the digit(s) actually displayed that is, when he keys any other digit than the one which was shown.

5. Adding errors (ADD) refer to adding one or more digits to a number.

6. Multiple errors (MPL) were scored when the S gave any combination of the five types of error described above.

All of the Ss' errors have been analyzed, tabulated, and totalled by categories, as shown in Table 9, Figures 11, 12, and 13.

By far the greatest number of errors occurred in the CUT category. This type of error increases in proportion to the relative performance criteria. Such a finding is consistent with our theory that, as test conditions become more difficult, the Ss concentrate their attention on the amount of information they can deal with, thus committing cutting errors by omitting final digits.

The multiple-type error (MPL) occurs mostly when longer numbers are exposed for extremely short times, as when eight digits are exposed simultaneously for 100 msec. It is particularly characteristic of the sequential mode when longer numbers were presented for any of the exposure times tested.

TABLE 9

Analysis of Types of Errors, By Display Modes, Number Lengths, and Exposure Times

Exposure Time	Simultaneous																	
	4-digit						6-digit						8-digit					
	CUT	INV	SKP	SUB	ADD	MPL	CUT	INV	SKP	SUB	ADD	MPL	CUT	INV	SKP	SUB	ADD	MPL
1000-msec.	2	2	8	3	2	2	38	17	8	8	3	24	117	4	6	10	0	63
500-msec.	2	2	4	6	0	4	76	10	11	11	2	23	159	2	6	5	0	48
100-msec.	32	2	8	29	4	20	129	3	5	5	3	57	107	2	5	5	2	96
All	36	6	20	38	6	26	243	30	24	24	8	104	383	8	17	20	2	207
	Sequential																	
1000-msec.	19	1	6	4	3	9	85	7	23	9	2	45	104	1	12	1	1	101
500-msec.	45	4	10	20	5	14	98	7	10	11	1	71	101	0	4	4	0	111
100-msec.	62	9	28	23	3	47	103	4	18	8	0	77	112	0	10	0	0	98
All	126	14	44	47	11	70	286	18	51	28	3	193	317	1	26	5	1	310
Total	162	20	64	85	17	96	529	48	75	52	11	297	700	9	43	25	3	517

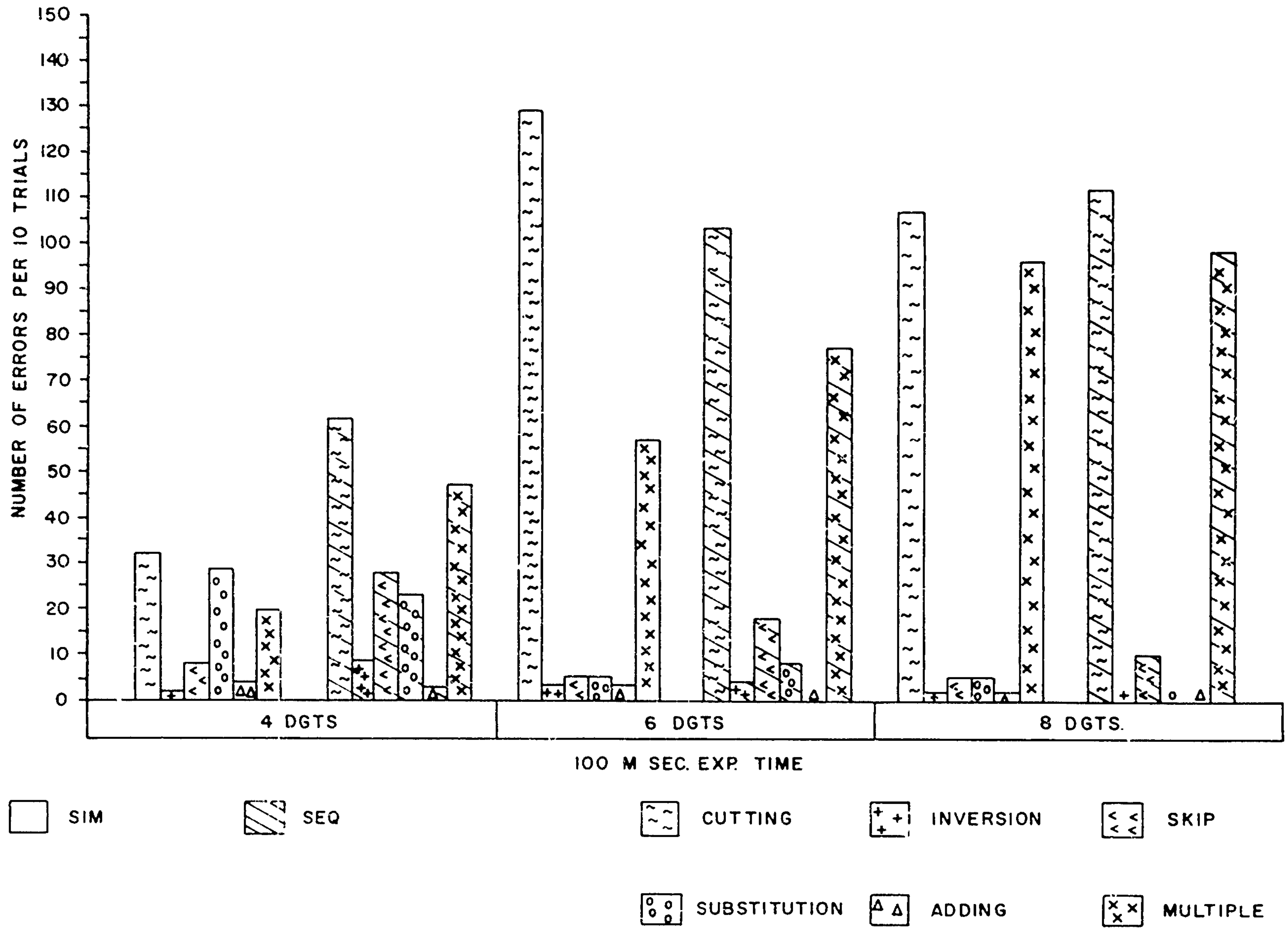

Fig. 11. Classification of types of errors for 100-msec. exposure time, by number lengths and display modes.

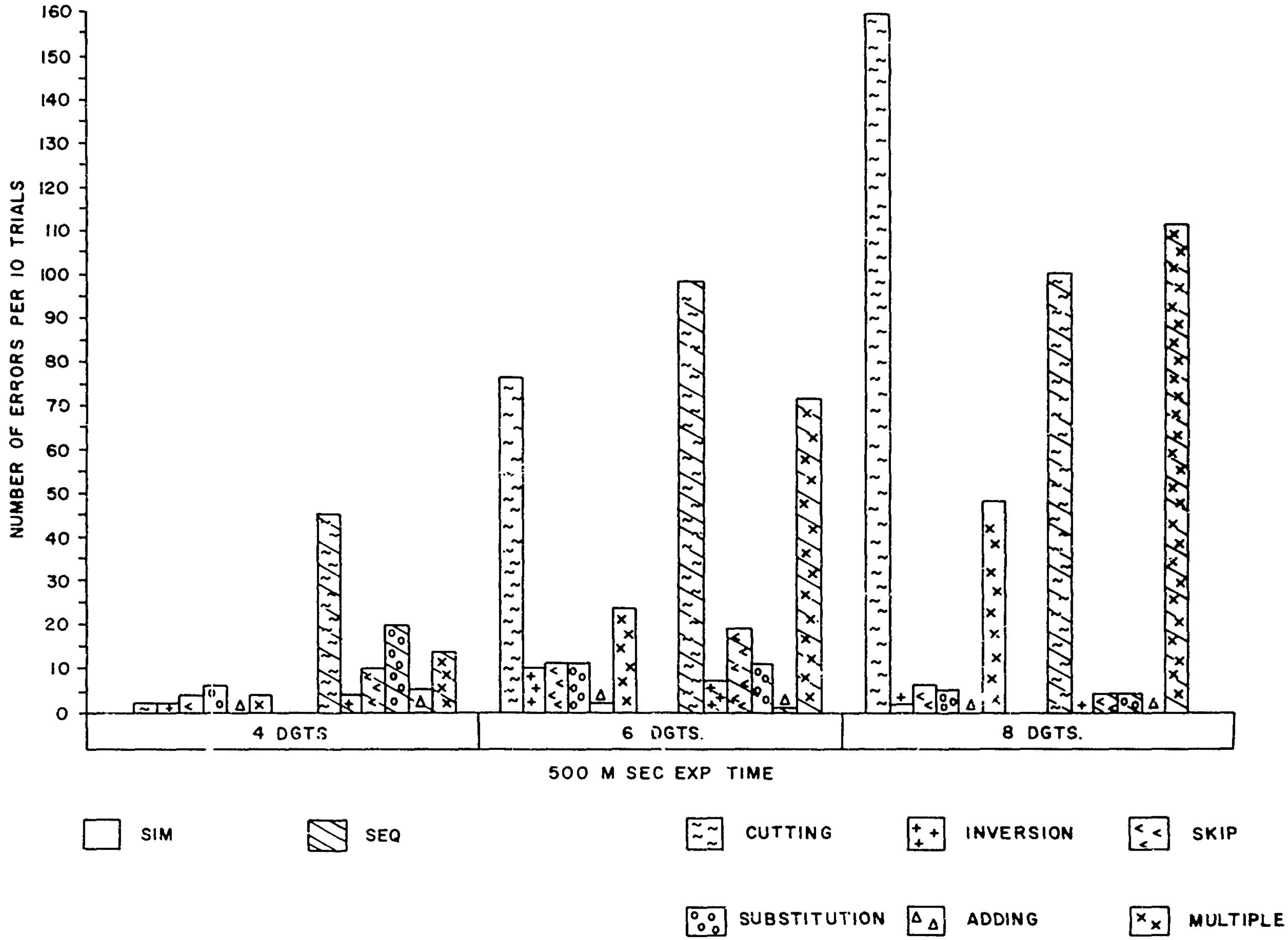

Fig. 12. Classification of types of errors for 500-msec. exposure time, by number lengths and display modes.

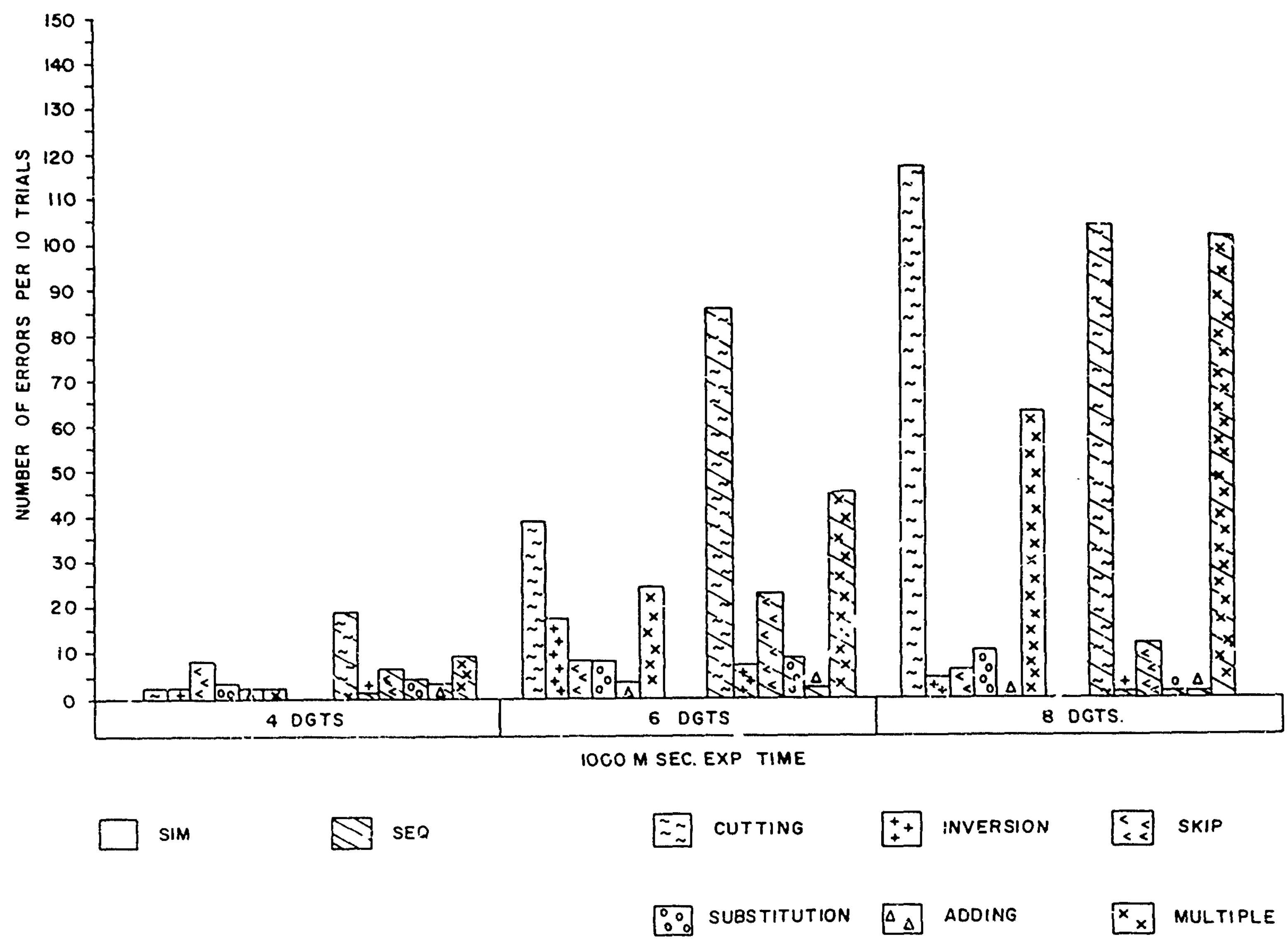

Fig. 13. Classification of types of errors for 1000-msec. exposure time, by number lengths and display modes.

There seems to be only one reasonable explanation for this effect: the exposure times (12.5, 60.3, and 125 msec. per digit) were simply too short, so Ss were unable to transfer accurately about half the time.

Interestingly, the number of cutting errors almost equalled the multiple errors. This seems to show that Ss were able, about half of the time, to follow the strategy of concentrating on the first four characters in longer numbers. Under these difficult conditions, their behavior on the other half of the trials must have been more or less unorganized, relying on guessing or applying sequences from earlier messages. Multiple errors may then be attributed to this breakdown of an organized approach—inability to maintain an organized strategy.

Next in frequency were the skipping (SKP) and substitution (SUB) errors. Under both modes, and almost independent of exposure times, these two types of errors occur relatively often with four-digit numbers. These errors appear to be related, and both types seem to indicate that the Ss are still attempting to maintain their transfer strategy. Despite their errors, the Ss were relatively successful in coping with short numbers. Although their performance tends to be stable, the test conditions apparently imposed strong-enough stress to confuse their strategy, producing comparable numbers of skipping and substitution errors.

Inversion-type errors are much less frequent than skips and substitutions, but all three types of errors characterize Ss who are fighting to transfer numbers effectively under adverse conditions.

Since inversions are the only errors that test whether digits are keyed in the correct order, inversions typify performance that is relatively well organized, yet not perfectly correct. The relative rarity of inversions in the present experiment may be interpreted in two conflicting ways. Few inversions may mean that order is considerably more resistant to disruption than content is. On the other hand, the small number of scorable inversions may simply arise because incorrect content makes it impossible to detect and label inversions.

There were very few adding errors (ADD). Nevertheless, a few adding errors did occur with short numbers in both display modes. Since these errors represent a certain amount of confusion in transferring even comparatively short, easy messages, they may have arisen from incompletely organized response strategies.

Evaluation in Terms of Information Theory

The transfer process can be seen from still another viewpoint. Applying concepts from information theory, the human operator may be considered as a communication channel. Thus the transfer task involves two interfaces with this human communication channel: input, or the numbers which are displayed as stimuli, and output, which constitutes the S's keying responses. If information is lost at either interface, the output will be in error. The two terminals of the transfer operation are the information source, which is the display, and the destination, which is the keyboard.

In this case, increasing the number length corresponds to increasing the amount of information which must be transferred. As input information increases, the individual would be expected to try to cope with the increase. But constantly increasing inputs would soon reach a limit, beyond which further increments would cause the Ss to make more and more errors. There would be a discrepancy between the input to the human receiver and the output from the receiver, and this discrepancy would grow larger and larger. In terms of information theory, this limit is analogous to the channel capacity of the human communication system.

Changing the time for which information was exposed at the source would probably produce a similar effect.

We may now define the relation between amount of information presented and length of presentation as the input rate. The input rate, then, depends on how much information is presented, and for how long. The human communication channel does not have infinite capacity; its maximum input rate is clearly limited in any real situation (Table 10). Presenting input information at faster rates than the channel can process means information will be lost and the output will contain errors.

TABLE 10

Qualitative Output: Average Number of Correct Digits

	Simultaneous			Sequential		
Exposure Time	4-digit	6-digit	8-digit	4-digit	6-digit	8-digit
1000-msec.	3.8	4.6	4.3	3.6	3.5	2.5
500-msec.	3.8	4.3	3.9	3.0	2.7	2.1
100-msec.	3.0	2.9	2.4	1.7	2.4	2.0

To clarify this discussion, consider the experimental task in informational terms. Since only the ten numerals were displayed, and each was equally likely to appear, information theory demonstrates that each digit represented 3.3 bits of information. Numbers of the same length always contain the same amount of information. With simultaneous display, the Ss were able to transfer an average of 13.2 bits, virtually regardless of how much input information there was (Figure 14). One might then generalize that, when people transfer purely numerical information, their channel capacity lies around 13 bits. This, however, was true only with sufficient long exposure times. When the experiment attempted to transfer information at higher input rates, the Ss actually transferred an average of 9.9 bits or less (Figure 15).

Although we know that the simultaneous and sequential modes gave considerably different outputs, both modes presented the same amount of input information, as defined in strictly informational terms. The difference evidently lies in what G. A. Miller's (1956) almost classical paper calls "chunks." Miller describes a recoding process in which Ss organize or group "the input information into familiar units or chunks." The immediate memory then stores these recoded chunks of information which, according to Miller, may contain varying numbers of bits per chunk. Sequential presentation seemingly interferes with recoding by forcing Ss to treat each digit as a separate chunk, thus drastically curtailing the number of bits per chunk. On the other hand, simultaneous presentation allows more opportunity for Ss to organize or recode information. It uses chunks more efficiently by incorporating more bits of information per chunk, so it improves transfer performance.

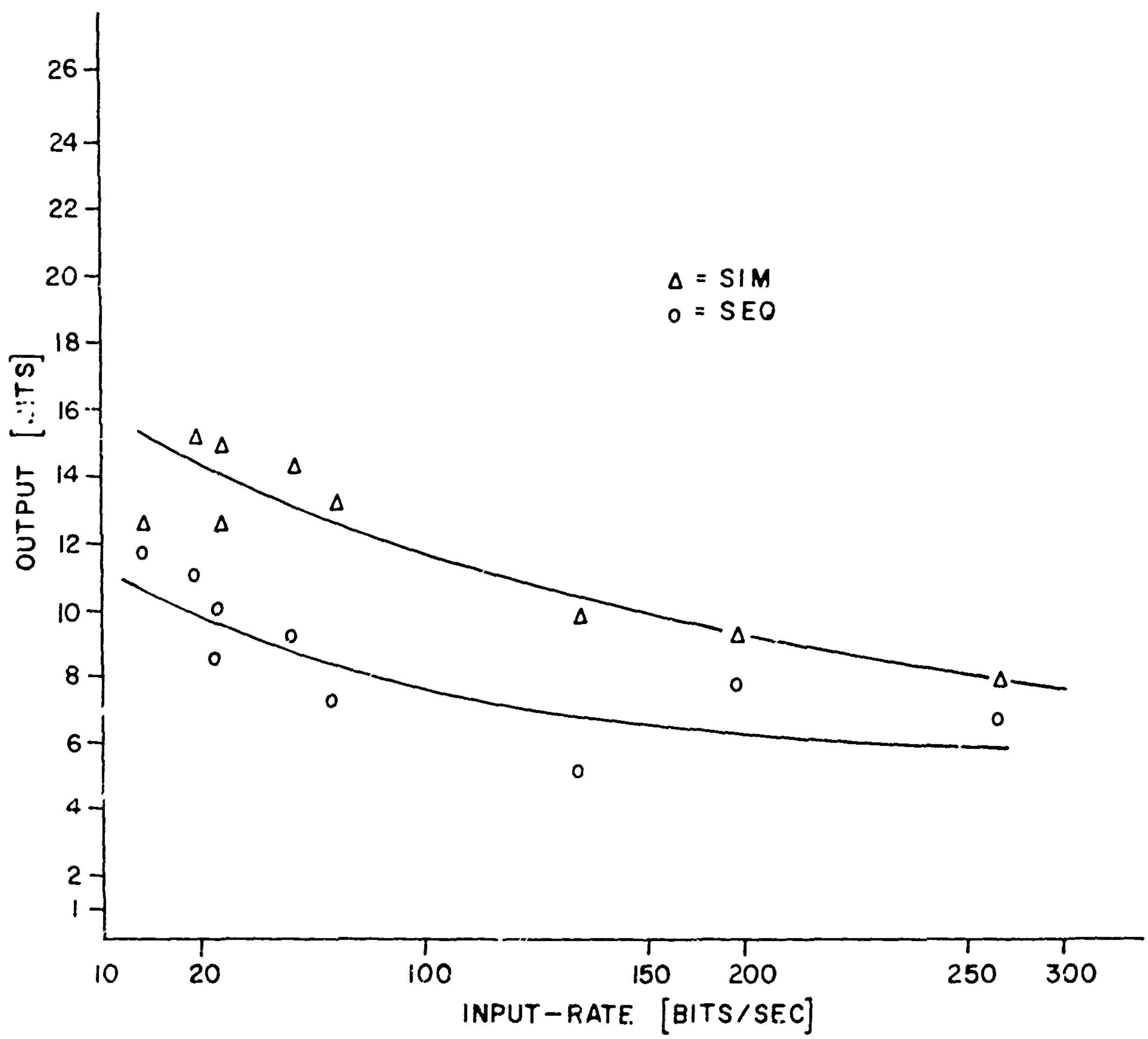

Fig. 14. Relationships between input rates and output rates, in bits, for Simultaneous and Sequential modes.

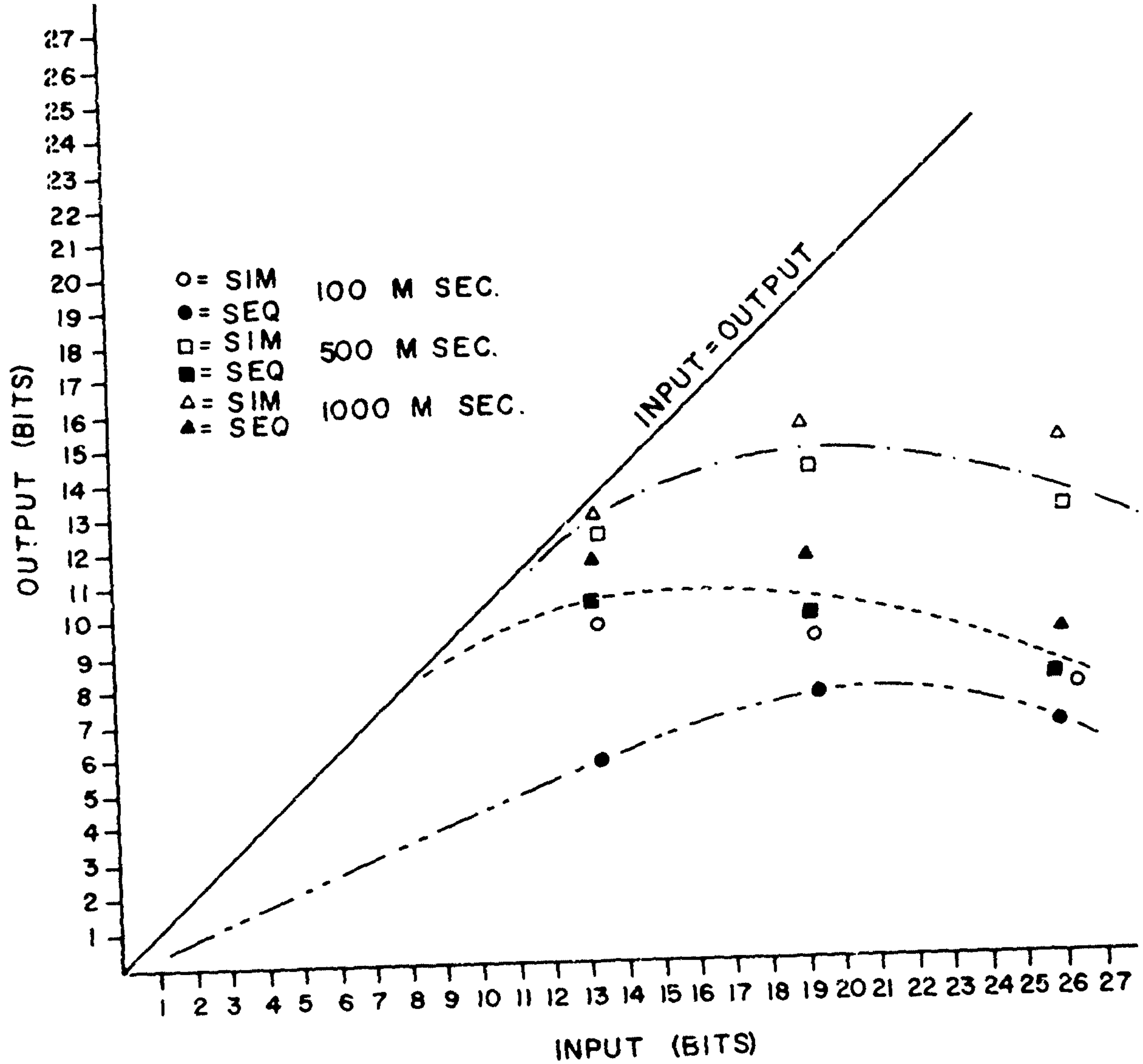

Fig. 15. Relationships between input rates and output rates, in bits, for each combination of exposure times and modes.

CONCLUSIONS

This experiment has verified previous investigators' hypotheses that information-transfer performance depends mainly on the amount of information that must be transferred. It has also extended the applicability of findings about short term memory—for example, Levy's (1971) demonstration that storage rate depends on speed of presenting data-by showing that the speed of data presentation has essentially similar effects on short-term memory and transfer tasks.

Two transfer responses were measured: reciting, in the pilot study, and keying, in the main experiment. Comparisons of performance show that transfer is more effective when Ss merely recite the numbers. Even untrained Ss could recite numbers much faster than keying them. Since keying is slower, and thus requires Ss to store numbers longer, it is not surprising that keying performance is less accurate. Even the smallest delays in transferring numbers make subjects more dependent on memory mechanisms which are strongly affected by time. Prolonging responses, even by seemingly trivial moments, can produce large and disproportionate degradation because the storage process is so sensitive to time.

Under the prevailing test conditions, the simultaneous mode transferred information more accurately than the sequential mode. The main advantage of the simultaneous mode seems to be allowing Ss some control over redundancy. With simultaneous presentation, the S can use the total exposure time to look at as many (or as few) digits as he wishes, in whatever order he prefers, he can even re-read digits. The Ss did not transfer numbers as accurately with sequential presentation. Findings in the literature indicate that less-trained Ss key symbols individually, rather than grouping them-and data from the pilot study revealed that Ss speak numbers as single digits-yet presenting characters sequentially is clearly not advantageous. It would appear that these choices to deal with single symbols are a constraint that Ss place on their output, but which is not consistent with nor favorable for--their input and storage processes.

The simultaneous mode leaves more latitude for the Ss to adopt individualized strategies. Thus, the S is free to develop more skilled transfer strategies, rather than being impeded by the externally imposed requirements of a presentation mode.

Within these strategies, "chunk building" seems to play an important role. To use their individual capacities better, Ss tend to divide messages into practical psychological units called "chunks." These units probably vary in size, depending on the individual's capacity and level of training, as well as personal factors like the ones seen in the pilot study, where Ss grouped digits quite individualistically when reciting them. These considerations indicate that, whenever an operator acquires information, he must "process" it, even if only by grouping digits. It is quite possible that this processing overlapped other activities under the test conditions, thus allowing Ss to take better advantage of redundancy in the simultaneous mode.

As compared to results of earlier studies, this experiment agrees that the short-term memory for non-redundant numbers can accommodate between three and four digits. Such a finding is also very plausible theoretically, and particularly in instances where the three or four digits given correctly are the first digits of a longer number.

Various findings in the literature suggest that the first digits of longer numbers are usually stronger in memory than later ones. Since it takes time to key numbers, there is also a differential delay; the Ss must key the first digits, which are easier to retrieve anyway, before they can begin keying later digits. Both factors–weaker initial memory trace and differential delay– would make it more difficult to transfer the final digits of longer numbers. Indeed, Conrad and Hull (1968) have demonstrated that errors in recalling seven-digit numbers mostly afflict the last four digits.

The results of this experiment suggest that there are two main sources of errors in transfer tasks:

1. Inadequate perceptual or storage capability.

2. Incidental factors which delay the response and prolong storage requirements.

Conrad (1966) describes this second error source as insufficient stimulus-response compatibility. It lengthens response times, as well as increasing errors, in the present experiment, time and errors were intimately related, so both would probably have been affected. Incompatible stimuli and responses can only increase the storage time that will be required, thus complicating what would have been a simple transfer task by requiring memory. Inevitably, performance deteriorates. Quite a variety of experiments agree that slowing the report rate degrades performance considerably. Difficulties in making responses can also distract the S, by forcing the S to divert part of his attention to an essentially unrelated, secondary task, incompatible responses reduce the resources available for transferring numbers. Previous research has established that recall is highly sensitive to interference from secondary tasks. Even if the perception itself were not effected, interference and other "noise" can obviously disturb the S's rehearsal.

There is little reason to suspect that Ss operated the wrong keys unintentionally, there were probably only occasional errors due to poor aiming. The strongest indication here is that the Ss' errors appear unrelated to effector processes. The errors seem to arise from perception and storage processes, as the classification of errors by categories has shown. The present experiment did not provide any kind of feedback nor any way for Ss to correct responses. Both of these features should be considered when designing actual equipment, since it is known that incorporating them usually improves performance.

Under the conditions of this test, it seems perfectly clear that the subjects performed better with simultaneous displays than with sequential ones. Still, certain findings suggest that the sequential mode might have advantages under different conditions. More specifically, future experiments should investigate whether sequential displays with different exposure times and grouping numbers according to several chunking methods would give better transfer.

Short-term memory experiments have found that simultaneous auditory and visual presentations can improve performance. This finding may well be true for transfer tasks as well, and future research should investigate whether audio displays or combination audio video displays would give better transfer.

Since short term memory tends to become involved in transfer, particularly with longer numbers, another way to enhance transfer is reducing demands on storage. For example, Levy et al. (1971) reported that the human memory stores numerals more effectively than letters. While this effect may arise from different vocabulary sizes– that is, fewer numbers than letters– future transfer experiments should determine whether a mixed alphanumeric vocabulary would give faster or more accurate transfer.

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